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VARIATION OF VISCOUS DRAG WITH FROUDE NUMBER

by

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Introduction

In the analysis of ship-model-resistance data, an assumed value for the viscous drag is subtracted from the measured value of the total resistance in order to obtain the wavemaking resistance. Most commonly this value is assumed to be given by a so-called correlation formula of the functional form

$$C_{VD} = f(\mathbb{R}) \tag{1}$$

where C_{VD} is a viscous-drag coefficient and $\mathbb{R}$ is the Reynolds number. More recently it has been proposed that the above relation be generalized to include the influence of ship form on the viscous drag; viz.,

$$C_{VD} = f(\mathbb{R}, \alpha) \tag{2}$$

in which α symbolizes the totality of hull-form parameters. A simple form of the function in (2) that has been suggested is

$$C_{VD} = a(\alpha)f(\mathbb{R}) + b(\alpha) \tag{3}$$

All of the foregoing assumptions ignore the effect on the viscous drag of the free surface and the concomitant surface waves generated by the hull. In the past this neglect was practically unavoidable, because a method for the separate determination of the viscous drag of a ship form had not yet been devised. But now that such a method has become available [1, 2, 3], it is of great interest to apply it to determine experimentally the actual variation of the viscous drag with Froude number, and so to evaluate the accuracy of the assumptions (1), (2), and (3).

The results obtained for the viscous drag of a Series 60 ship model are reported in the present note. This work was performed under the sponsor-

*Numbers in brackets refer to references at the end of this note.

ship of the Bureau of Ships Fundamental Hydromechanics Research Program, administered by the David Taylor Model Basin.

Equipment

The equipment used to survey the wake of a ship model was similar to that described in Reference [2]. For the present tests a new pitot rake, containing about twice as many stagnation and piezometric tubes, was built. This rake contains 17 stagnation tubes, and 16 piezometric tubes with 6 1/64-inch-diameter side holes on each, mounted alternately on the rake, 1/10 foot apart. These were mounted on a 1/2 x 4-1/4-foot board, 1/10 foot thick, with front edge streamlined. Another stagnation tube was attached to the carriage in front of the ship model to measure the undisturbed total head. These tubes were made of brass, 3/16 inch in diameter. The rake could be set at various longitudinal, lateral, and vertical positions behind the ship model.

The pressure readings were transmitted through plastic tubes to a pair of air-water differential manometers, a description of which, as a single manometer, was given in Reference [2]. The second manometer of the pair was built for the present tests. The positions of the menisci on the manometer board were recorded photographically by means of a pair of 35-mm cameras.

The model used in the present tests was also the same one as was used in Reference [2], a 10-foot Series 60 model of 0.60 block coefficient. A row of pins, 1/8 inch in diameter and 1/10 inch high, spaced at 1/2-inch intervals, was attached to the hull at a transverse section 1 foot longitudinally from the bow, measured from the intersection of the bow with the waterline. The towing arrangement used restrained the model to move in a direction parallel to the channel, but left it free to sink and trim.

Procedure

All the wake-survey measurements were taken in a transverse plane at a distance of 1/2 model length behind the model, at seven different speeds corresponding to the speed-length ratios $V/\sqrt{L} = 0.05, 0.6, \ldots 1.1$, where V is in knots and L is the model length in feet. At each speed, 374 total-head readings and 352 pressure-head readings, at horizontal and vertical intervals of 0.1 foot, were taken. Runs were made at time intervals of 8 minutes.

The water temperatures, measured every half day, before and after testing, at the water surface and at a depth of 2 feet, were the same at both depths. In the course of the tests the temperature varied between 59.7° and 60.5° F.

The water surface in the plane of measurements across the wake was found to vary slightly from the level of the undisturbed surface. This variation was measured and its mean level was used in evaluating the viscous-drag integral.

After the wake-survey measurements had been completed, two additional series of tests were made over the same range of speeds, one to determine the total resistance of the model, the other to photograph the profile of the free water surface along the surface of the hull.

Results and Discussion

The coefficients of viscous drag C_{VD} and of total resistance C_t, and the values from the 1957 ITTC correlation formula C_f, are graphed against speed-length ratio in Fig. 1. Also shown in the figure is the curve of wetted-surface area, calculated from the observed water-surface profile along the hull.

It is seen that the measured viscous drag deviates considerably from the correlation line, varying from about 10 percent below it to about 5 percent above. The curve of wetted-surface area was obtained for the purpose of determining whether there was a correlation between its variation and that of the viscous drag, but there appears to be no obvious connection between the curves of these quantities.

Values of the residuary-resistance coefficient, $C_t - C_f$, and the wavemaking resistance, $C_t - C_{VD}$, are graphed against the Froude number $v/\sqrt{Lg}$ in Fig. 2. In contrast with the results of Ward [4], Eggers [5], and Gadd and Hogben [6], whose values for the wavemaking-resistance coefficients were about half of the residuary-resistance coefficient, the present values for the wavemaking resistance are greater than the residuary for Froude numbers less than 0.26, and slightly less than the residuary at larger Froude numbers. The theory for the direct determination of wavemaking resistance by means of surface-profile measurements, on which the results of the aforementioned investigators [4, 5, 6] are based, is probably at fault. It is suggested that it may be necessary to reexamine the theory of the direct determination of wave-making resistance so as to take into account the presence of vorticity in the wake.

An important difference between the curves of wavemaking and residuary resistance in Fig. 2 is that the hump and hollow in the former curve at $\mathbb{F}$ = 0.238 and 0.258 do not appear in the latter. The occurrence of a hump and hollow at about these values of the Froude number is also predicted by wavemaking-resistance theory; see Fig. 12 of Reference [6].

The unexpectedly sinuous variation of the viscous-drag coefficient raises the possibility that ship forms may have widely varying viscous-drag curves, and that it may be necessary to take into account the characteristic curves of both wavemaking- and viscous-drag-resistance coefficients in judging the merit of a particular hull form. In order to resolve this interesting possibility it will be necessary to measure the viscous-drag curves of a family of ship forms.

Assuming that the wavemaking-resistance coefficient obtained with a ship model is applicable to the prototype at the corresponding Froude number, the difficult problem of determining the viscous drag of the prototype still remains. For this purpose several approaches suggest themselves. First, it would be desirable to obtain the viscous-drag curves of a family of geosims. Secondly, the viscous drag should be measured on a full-scale trial, possibly by towing a grid of total-head- and pressure-measuring devices behind a ship. Thirdly, the procedures that have recently been developed for computing turbulent boundary layers on three-dimensional forms should be applied to calculate the viscous drag of a ship, both in model scale, for which laboratory data would be available for comparison with the calculations, and also in full scale. The variation of viscous drag with the Froude number found in the present work indicates that such calculations would have to be based on the actual pressure gradients along the hull, or, if it is attempted to compute these also, on the velocity distribution along the hull, taking into account the presence of the disturbed free surface, the boundary layer, and the wake.

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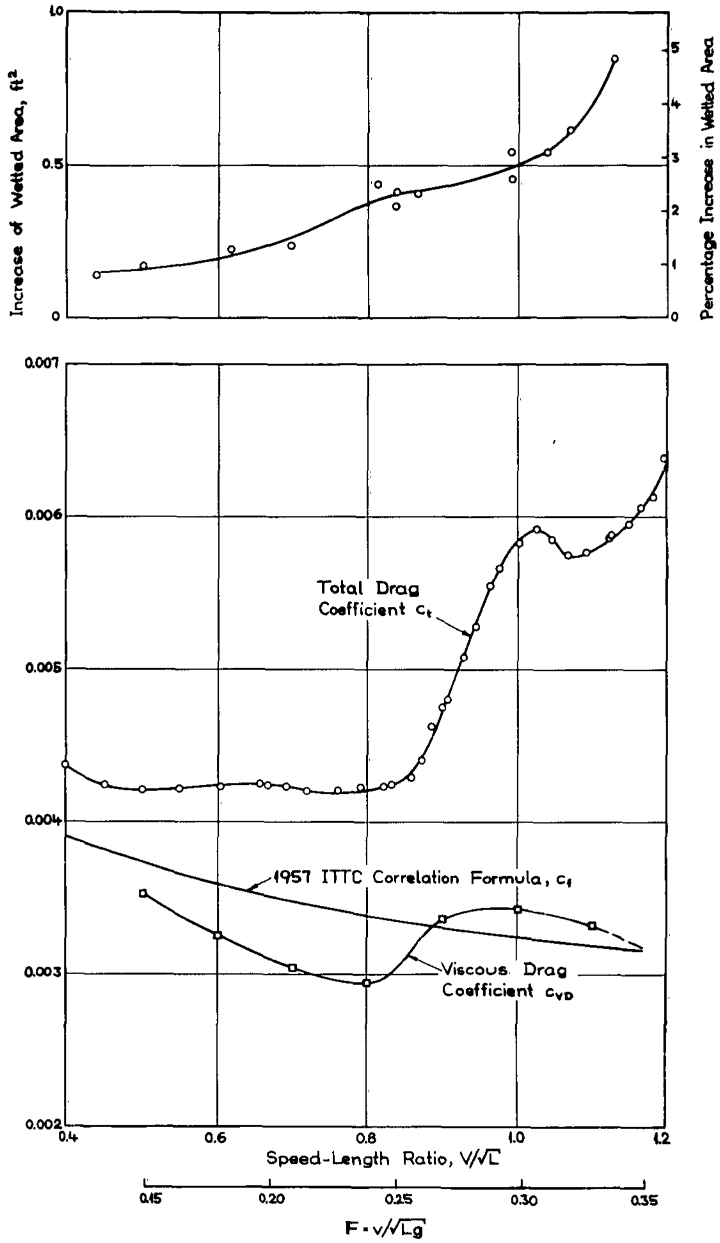

FIG. 1 TOTAL AND VISCOUS DRAG AND WETTED SURFACE AREA FOR A SERIES 60 SHIP MODEL

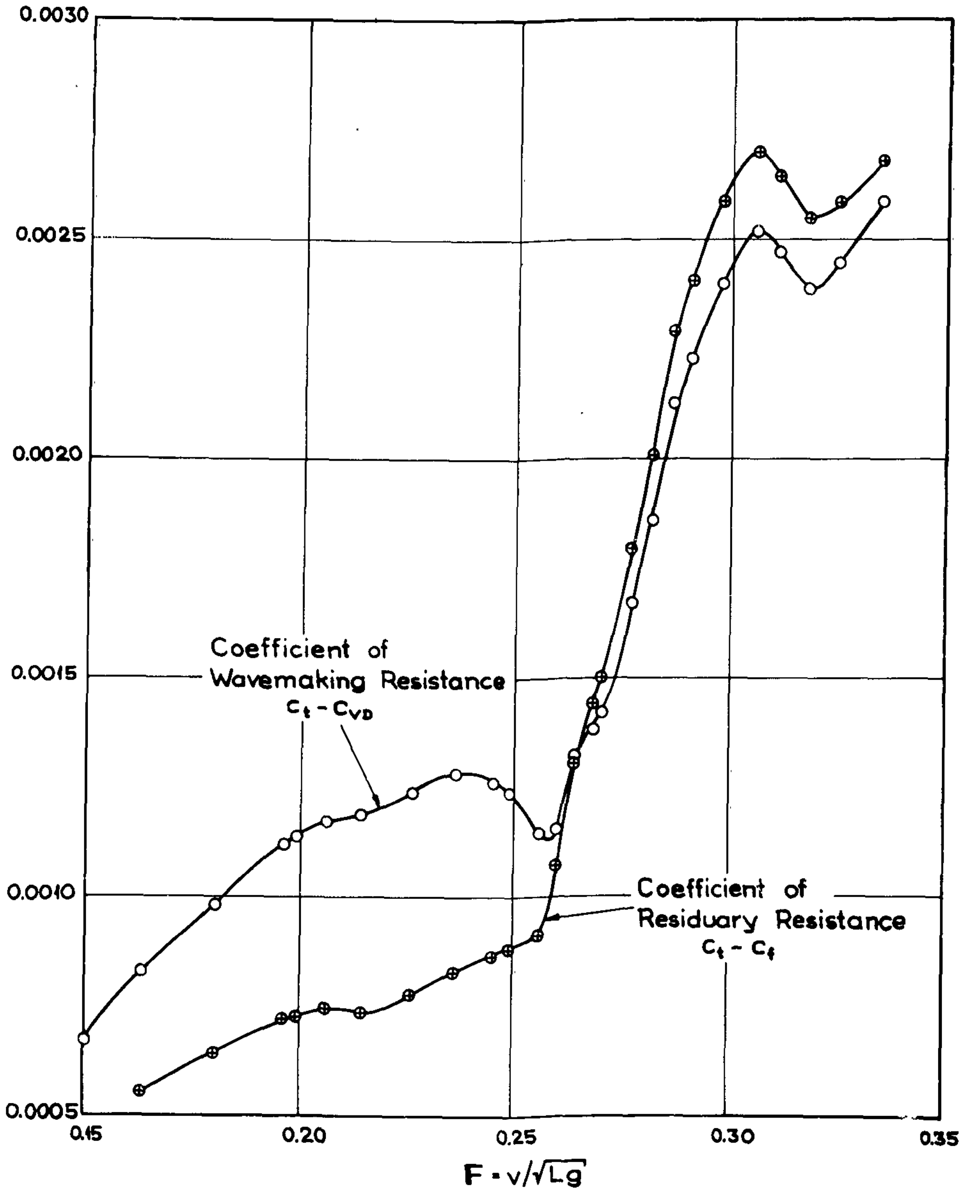

FIG. 2 COEFFICIENTS OF WAVEMAKING AND RESIDUARY RESISTANCE